

Method, Apparatus and System for Transferring Heat**Technical Field**

An invention is disclosed relating to a method, apparatus and system for transferring heat. The invention finds particular application as a desorption cooler, using the heat of one fluid (gas or liquid) to cool another fluid and, whilst being described in this context, is not so limited. In addition, the invention can be applied in reverse, to enhance the cooling of a heated fluid. In any case, the invention finds application in a broad range of industries and contexts.

Background Art

Many industries discharge warm and hot process and waste gases to atmosphere such that the heat energy is lost. This can also result in a contribution to atmospheric warming. Warm liquids such as waste waters can also be released to the environment. It would be desirable if some of this wasted heat energy could be captured and utilised in that industry or elsewhere.

US 5,522,228 discloses apparatus for the production of cold by the adsorption and desorption of carbon dioxide. The apparatus comprises two vessels 10,11 packed with activated carbon and zeolite respectively, and connected by a conduit 12 having a valve 13. A heat exchanger 14 is provided around vessel 10 and a heater 15 is provided around vessel 11.

In operation, vessel 10 is cooled to -50°C, with the zeolite in vessel 11 at 190°C. The valve 13 is opened and the carbon dioxide desorbs from the activated carbon, which somehow warms the vessel 10 up to 0°C. However, as desorption would extract heat from the activated carbon, presumably a heated fluid is passed through heat exchanger 14 to warm the vessel 10 up to 0°C. The desorbed carbon dioxide passes to vessel 11 and is adsorbed by the zeolite, which cools to 45°C. Again, as adsorption would

heat the zeolite, presumably some type of cooling is employed to cool the vessel 11 to 45°C.

The valve is then closed, and vessel 10 is allowed to warm from 0°C to 30°C (ambient temperature). At the same 5 time vessel 11 is heated by heater 15 from 45°C to 70°C.

The valve is then opened, and vessel 11 is heated from 70°C to 200°C by heater 15, which desorbs the carbon dioxide from the zeolite and causes it to pass to and adsorb on the activated carbon in vessel 10. This causes 10 the activated carbon to cool from 30°C to -40°C, presumably by circulating a cooling fluid in heat exchanger 14, as adsorption would heat the activated carbon (ie. thermodynamically self cooling to -40°C is impossible due to the liberation of heat of adsorption).

15 The heating of vessel 11 is then stopped and it is allowed to cool from 200°C to 190°C. With the valve open, this causes a pressure drop in both vessels 10,11 and the activated carbon drops in temperature from -40°C to -50°C to complete the cycle. This cold can then be utilised by 20 passing a fluid through exchanger 14.

In the apparatus of US 5,522,228 valve 13 is essential because it is required to maintain the carbon dioxide pressure in vessel 10 during regeneration of the zeolite. If the valve is not closed carbon dioxide will 25 simply desorb from the carbon and pass to the zeolite at the time of pre-cooling of vessel 10, so that little cooling would be observed during the cooling phase.

Contrary to the teaching of US 5,522,228, the present invention provides a method, apparatus and system 30 which does not require the complexities of periodic valve closure/opening between two vessels, nor start temperatures in the vicinity of -50°C.

Summary of the Invention

In a first aspect the present invention provides a 35 method for transferring heat using first and second gas adsorbent materials. As opposed to US 5,522,228, in the method of the present invention the second material is

relatively thermally isolated from but in continuous gas communication with the first material. The method comprises the steps of:

- (i) heating the first material so as to desorb a gas adsorbed onto the first material whereby the gas passes to and is adsorbed onto the second material; and
- 5 (ii) cooling the first material so that the gas is desorbed from the second material and passes therefrom to be re-adsorbed onto the first material;
- 10 whereby the second material is cooled by desorption therefrom of the gas.

Advantageously a hot fluid stream (eg. a waste gas or process liquid) can be used to heat the first material so as to desorb the gas adsorbed onto the first material and, 15 at the same time, the hot fluid stream can be cooled. Then another fluid stream that requires cooling can be brought into thermal communication with the second material so that, when the second material is cooled by desorption therefrom of the gas, the other fluid stream can be 20 cooled. In other words, advantageously the heat of one stream can be used to cool another.

In addition, by ensuring that the second material is in continuous gas communication with the first material, a number of system, apparatus and operating simplifications 25 and efficiency improvements follow, especially when compared to the apparatus of US 5,522,228, as will become apparent hereafter. For example, the method can be commenced at ambient temperatures and does not require an external cooling source. In addition, because of the 30 continuous gas communication, pressure changes during operation are immediately translated and accommodated, and do not require additional arrangements such as valving, external heaters etc to compensate therefore.

In this specification, the expression "relatively 35 thermally isolated" is intended to mean that the first and second adsorbent materials are sufficiently thermally isolated such that one can be heated or cooled without

affecting the other to an extent that prevents a required/desired cooling desorption (or the reverse) from being attained. In addition, thermal isolation can be enhanced by spacing and/or insulating the first and second
5 adsorbent materials from each other.

Typically in step (i) the first material is heated by heat transfer from a relatively hotter fluid stream (eg. via a heat exchange configuration). The hotter fluid stream can be a process waste gas or liquid.

10 Optionally in step (i), whilst the first material is being heated, the second material is cooled relative to the first material by heat transfer with a cooling fluid stream. This cooling further facilitates adsorption of gas onto the second material. The cooling fluid stream can be
15 eg. a stream of ambient air.

Typically in step (ii) the first material is cooled relative to the second material by heat transfer to ambient or by heat transfer with a cooling fluid stream. Again, the cooling fluid stream can be a stream of ambient
20 air.

Typically, in step (ii) whilst the second material is being cooled by desorption therefrom of the gas, it is used to cool another fluid (gas or liquid) stream (eg. via a heat exchange configuration). Typically the other fluid
25 is a process gas or liquid requiring or benefiting from cooling, and may be eg. ambient air to be cooled and used in the process.

The fluids in each of the streams can be gas or liquid. For example, as stated above, the hot fluid stream
30 can be a process waste or exhaust gas, the heat of which is usually otherwise wasted. In addition, heat transfer with a cooling fluid stream is usually achieved by selectively bringing the first and second materials into thermal communication with eg. a stream of ambient air
35 (eg. via the same or a different heat exchange configuration as used for the fluid hot or cooled fluid stream respectively).

In addition, typically once gas desorption from the second material has reached completion, the second material is allowed to be slightly heated by heat transfer from the other fluid stream, and so that the second 5 material is heated just enough to restore its temperature to a level which corresponds with its temperature in step (i) prior to gas adsorption thereon, thereby completing a cycle.

Typically the first gas adsorbent material has a 10 different adsorptivity to the second gas adsorbent material. In use, this helps provide a driving force for gas movement between the materials. Typically the first gas adsorbent material is a different material to the second gas adsorbent material. In this regard, the first 15 adsorbent material can comprise a molecular sieve and the second adsorbent material can comprise an activated powder. Alternatively, the first and second adsorbent materials can each comprise a molecular sieve, or each comprise an activated powder, but of different 20 adsorptivities. The or each molecular sieve can be a zeolite, the or each activated powder can be an activated carbon, and the gas employed with the first and second adsorbent materials can be carbon dioxide.

Typically this gas is pressurised relative to ambient 25 pressure. A typical operating pressure in the method for the gas is around 0.5 MPa.

Typically, prior to commencing step (i) of the method, the gas and first and second materials are generally at ambient temperature.

30 In a second aspect the present invention provides heat transfer apparatus comprising a chamber having a first portion which contains a first adsorbent material and a second portion which contains a second adsorbent material, the apparatus characterised in that the portions 35 are connected so as to always allow continuous gaseous communication therebetween and are relatively thermally isolated from each other.

The inventor has observed that an apparatus having thermally isolated portions can advantageously achieve desorption cooling (and the reverse) whilst the first and second adsorbent materials are always maintained in

5 continuous gaseous communication (ie. without requiring a valve or stop therebetween to achieve a desorption cooling cycle). This provides, for example, a simplification over the apparatus of US 5,522,228, which requires a valve. In addition, because a valve is not present or required in

10 the apparatus, pressures in the first and second chamber portions automatically equilibrate.

Typically the first and second portions are joined by a section which is adapted to minimise conductive heat transfer between the first and second portions whilst

15 allowing the continuous gaseous communication between the portions. The section is usually a conduit having a relatively smaller width (eg. smaller diameter, or smaller effective diameter) than the width (eg. diameter or effective diameter) of the first and second chamber

20 portions adjacent thereto. Because the conduit has a smaller width it has less surface area/dimension for heat transfer, and yet still provides for continuous gas communication between the portions.

Typically the first and second chamber portions and

25 the conduit are each tubular, whilst typically the first and second chamber portions are approximately the same size.

Typically one or more heat transfer elements are arranged in each of the first and second chamber portions

30 together with the first and second adsorbent materials. Typically each heat transfer element comprises a metal wire mesh that enhances thermal communication between an exterior of the chamber portion (via a wall of the chamber portion) and the adsorbent material therein. Surprisingly

35 and advantageously, the heat transfer elements have also been found to enhance the mass transfer rate of the gas

(eg. carbon dioxide) through each of the first and second adsorbent materials.

Typically the first and second materials are each packed into a respective portion of the chamber. Typically
5 the first and second materials are as defined in the first aspect of the invention.

Typically the first and second chamber portions are each adapted to be positioned midstream of a respective flow of fluid, to more effectively transfer heat between
10 the respective fluid and portion.

In a third aspect the present invention provides a system for continuously transferring heat from a first fluid stream and for continuously cooling a second fluid stream. The system comprises first and second apparatus each able to be brought into thermal communication with the first and second fluid streams. Each apparatus comprises a chamber having separated first and second adsorbent materials, and each apparatus is operable in the following stages whereby:

20 (1) the first material is heated by thermal communication with the first fluid stream so as to desorb a gas adsorbed onto the first material whereby the gas passes to and is adsorbed onto the second material; and

25 (2) the first material is cooled so that the gas is desorbed from the second material and passes therefrom to be re-adsorbed onto the first material, with the second material being cooled by desorption therefrom of the gas, and the second fluid stream being cooled by thermal communication with the second material.

30 The system is characterised in that:

- whilst the first apparatus is operated under stage (1) to heat the first material of the first apparatus using the first fluid stream, the second apparatus can be operated under stage (2) to cool the second fluid stream
35 by desorption of the gas from the second material of the second apparatus; and then

- the first fluid stream can be directed to the second apparatus and operated under stage (1) of the second apparatus, and the second fluid stream can be directed to the first apparatus and operated under stage (2) of the
5 first apparatus.

In this way, the system advantageously provides for continuous transfer of heat from the first fluid stream and continuous cooling of the second fluid stream. By switching the first and second fluid streams, the system
10 allows, for example, the method and apparatus of the first and second aspects to be operated in a continuous rather than interrupted desorption cooling process (and the reverse).

Typically the system comprises a plurality of first
15 apparatus and a plurality of second apparatus, and typically the first and second apparatus are operated in parallel.

Typically the system further comprises valving for selectively switching the flow of the first and second
20 fluid streams respectively between the first and second apparatus and the second and first apparatus, to maintain a continuous transfer of heat from the first fluid stream and a continuous cooling of the second fluid stream. The valving can also be used to switch a cooling fluid stream
25 between the first and second apparatus, such as a stream of ambient air.

In the system, typically each of the first and second apparatus is as defined in the second aspect and typically each apparatus is operated using the method of the first
30 aspect.

Brief Description of the Drawings

Notwithstanding any other forms which may fall within the scope of the present invention, preferred forms of the
35 invention will now be described, by way of example only, and with reference to the accompanying drawings in which:

- Figure 1 shows a schematic view of a desorption chiller module according to the invention;
- Figure 2 shows a schematic view of a desorption cooling system according to the invention and employing a plurality of the desorption chiller modules of Figure 1;
- 5 - Figures 3a and 3b show schematic side and plan views of a demonstration unit for use in desorption cooling of a gas;
- Figure 4 is a graph plotting temperature against time for the temperature locations T8, T4 and T6 for the regenerator of the unit of Figure 3;
- Figure 5 is a graph plotting temperature against time for the temperature locations T5 and T3 for the desorption cooler of the unit of Figure 3; and
- 10 - Figure 6 is a graph plotting temperature against time for the temperature locations T1, T6, T4, T3 and T5 for the demonstration unit of Figure 3.

Detailed Description of Specific Embodiments

20 In a typical mode of use, a method, apparatus and system according to the invention is used to transfer heat energy (eg. waste heat) from a gas or liquid stream to achieve a separate cooling purpose (eg. the cooling of another separate fluid stream).

25 Referring now to Figure 1, a simple apparatus according to the invention is shown in the form of a desorption chiller module. The module comprises a sealed vessel 10 having two cylindrical chambers (eg. tubes, such as stainless steel tubes), being a regenerator chamber 12 and a desorption cooler chamber 14. The chambers are connected by a joining section in the form of a narrower (eg. smaller diameter) conduit or neck 16 (such as a smaller diameter tube). To provide for greater thermal isolation of the chambers 12,14 the conduit 16 can be 30 formed from a material having lesser thermal conductivity than the chamber walls (eg. a less thermally conductive

stainless steel) and is typically welded to the chamber walls to seal the vessel 10.

Regenerator chamber 12 is packed with a first adsorbent material, typically in the form of a molecular sieve (eg. a zeolite such as a 13X zeolite) and the desorption cooler chamber 14 is packed with either a different second adsorbent material (eg. a surface activated powder such as activated carbon) or the same material but having a different adsorptivity (eg. another type of zeolite but having, for example, a lesser adsorptivity eg. 10A, 8A, 5A zeolites or another type of 13X zeolite).

One or more heat transfer elements in the form of a plurality of discrete metal wire mesh panels are preferably arranged in each of the chambers 12&14, together with the first and second adsorbent materials (ie. the panels are dispersed through the adsorbent material). The panels are typically formed from a material not reactive to the gas and materials in vessel 10, such as stainless steel, brass, aluminium or copper, and of a material having sufficient thermal conductivity. The panels function to enhance thermal conductivity between the adsorbent material and the wall and thus exterior of each chamber. In addition, the present inventor has surprisingly and advantageously discovered that the panels enhance the mass transfer rate of carbon dioxide through each of the first and second adsorbent materials.

The sealed vessel 10 further comprises a suitable pressurised gas, typically carbon dioxide because of its abundance and ease of use; but other gases can be used such as refrigerants, ammonia, alcohol, water (steam), nitrogen etc in combination with adsorbents suitable to the gas.

In accordance with the invention, the sealed vessel 10 is configured such that the gas can pass continuously and unhinderedly between each of the chambers 12,14 via the conduit 16. Advantageously no valving or additional

flow control is provided or required and, as a further advantage, the sealed vessel has no moving parts.

In addition, the sealed vessel 10 is typically configured so that the desorption cooler chamber 14 (housing the second adsorbent material) is, at least to an operable extent, thermally isolated from the regenerator chamber 12 (housing the first adsorbent material). This is optimally achieved by employing the narrower conduit 16 to connect but space apart the chambers. However, thermal isolation can be further enhanced by employing appropriately positioned insulation, including insulation barriers and baffles in, around and/or between the chambers (see eg. the system of Figure 2 described below).

In a first mode of use, the first adsorbent material is selected to have a higher adsorptivity for the vessel gas than the second adsorbent material. Starting at ambient temperature, it is observed that a greater proportion or a bulk of the vessel gas is adsorbed on the first material.

In the first mode of use, and in a first step, the regenerator chamber 12 is contacted with a relatively hot gas stream (eg. a process waste gas) by arranging the regenerator chamber in the centre or midpoint of the hot gas stream and so that the first adsorbent material is heated. The hot gas stream can be passed over, around or even through chamber 12 (eg. via one or more pipes/tubes extending through chamber 12). As the first material heats up, adsorbed gas (eg. carbon dioxide) is desorbed therefrom and the gas pressure in the vessel increases. Because of the relative thermal isolation of the desorption cooler chamber 14, there is a driving force for the carbon dioxide to pass from chamber 12 into the chamber 14 via the conduit 16 and be adsorbed onto the relatively cooler second material (eg. activated carbon). During this adsorption the second material becomes slightly heated. The tendency of the gas to adsorb onto the second material can be enhanced by arranging the

chamber 14 in the centre or midpoint of a cooling gas stream (eg. a stream of ambient air) such that the second material is further cooled relative to the first material.

The first material (eg. zeolite molecular sieve) 5 remains relatively heated whilst in thermal communication with the hot gas stream, so that there is no driving force for re-adsorption thereon of the gas in the vessel 10.

In the first mode of use, and in a second subsequent step, the regenerator chamber 12 is then cooled (eg. by 10 stopping or redirecting the flow of hot gas and, more typically, by contacting the chamber 12 with a cooling gas stream (eg. ambient air)). As chamber 12 cools, the first material cools and the pressure of carbon dioxide in the vessel is reduced. This then provides a driving force for 15 gas to pass back to the regenerator chamber 12 and be re-adsorbed onto the first material. In this regard, the gas is desorbed from the second material and passes from chamber 14 via conduit 16 into chamber 12 and re-adsorbs onto the first material.

Advantageously, the desorption of the carbon dioxide 20 from the second material in chamber 14 cools the second adsorbent material (ie. the gas needs to extract heat from the material during its desorption) and thus cools the chamber 14 and the walls thereof. In fact, the inventor 25 has observed that the second chamber can be cooled by greater than 10 °C below ambient temperature as gas desorption progresses.

Now the same or another fluid stream can be passed over, around or even through chamber 14 (eg. through one 30 or more heat exchange pipes/tubes arranged therethrough), so that the other fluid stream is cooled. Thus, cooled chamber 14 can be used, for example, to pre-cool a stream for eg. an engine or gas turbine, or to provide cooling air for air conditioning etc. In this way, a hot process 35 fluid (eg. waste gas) can be used to cool another process fluid requiring or benefiting from cooling.

An optimal application of the invention is in electricity generators, where a hot waste (exhaust) gas from eg. coal or fuel combustion is used to pre-cool a gas stream fed to a turbine etc.

5 Referring now to Figure 2, where like reference numerals are used to denote similar or like parts, a desorption cooling system 20 according to the invention is depicted. The system can provide for continuous desorption cooling in accordance with the invention.

10 The system 20 employs a plurality of the sealed desorption chiller vessels 10 of Figure 1, the vessels arranged in parallel, in each of parallel module banks A and B. Each module bank is in turn arranged in a respective bank vessel 22. Further, each bank vessel 22
15 comprises a thermal barrier wall 24 positioned to divide each regenerator chamber 12 from its respective desorption cooler chamber 14 (except for conduit 16, which extends through wall 24). Barrier wall 24 thus further enhances the thermal isolation of chambers 12 and 14. Barrier wall
20 24 can also be formed from and/or lined with an insulating material. In addition, barrier wall 24 now defines a regenerator chamber 26 and a desorption cooler chamber 28 in each bank vessel 22.

At opposite ends of system 20 four-way valves 30,30' 25 are arranged for selectively directing fluids (eg. gases) into the bank vessels 22 of the module banks A and B. In this regard, four-way valve 30 can selectively direct a hot process gas 32 (eg. a hot air stream) into one of the regenerator chambers 26, whilst simultaneously directing a
30 cooling gas 34 (eg. an ambient air stream) into the other of the regenerator chambers 26.

Similarly, four-way valve 30' can selectively direct a process gas requiring cooling (eg. an air stream) into one of the desorption cooler chambers 28, whilst
35 simultaneously directing a cooling gas 36 (eg. an ambient air stream) into the other of the desorption cooler chambers 28. However, in the system of Figure 2, the

stream of cooling gas 36 is split and directed into both desorption cooler chambers 28, one stream for a cooling purpose (ie. in one of the chambers 28) and the other stream to be cooled to produce a chilled air stream 38
5 (ie. selectively retrieved from one of the chambers 28). Thereafter, the chilled air stream is selectively retrieved from the other of the chambers 28, and so on in a continuous manner.

The four-way valves 30,30' are controlled such that
10 eg. whilst the regenerator chamber 26 of module A is receiving hot process gas 32 therein to facilitate gas desorption from each of the first adsorbent materials, the regenerator chamber 26 of module B is receiving cooling gas 34 therein to facilitate gas adsorption on each of the
15 first adsorbent materials (ie. as controlled by four-way valve 30). Simultaneously, the desorption cooler 28 of module A is receiving cooling gas 36 therein to facilitate gas adsorption on each of the second adsorbent materials, and the desorption cooler 28 of module B is receiving to-
20 be-chilled gas 36 therein as gas desorption from each of the second adsorbent materials takes place (ie. as controlled by four-way valve 30').

At the same predetermined time for each module (eg.
when the hot gas heat transfer and/or gas chilling starts
25 to move from steady state) the gas flows for each of the four-way valves 30,30' are switched, so that the subsequent process stage can take place in each of the modules A & B. In this way, the system 20 advantageously provides for the continuous transfer of heat from the hot process gas 32 and for the continuous chilling of the gas 36. Further, by switching the gas streams, the system allows for continuous as opposed to interrupted desorption cooling. Alternatively, the system can facilitate a process that is the reverse of desorption cooling.
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Non-limiting Examples of the method, apparatus and system will now be described.

EXAMPLE 1.

The desorption chiller module of Figure 1 was tested and then calculated to have a coefficient of performance (COP) of 0.22 (cf a theoretical COP of less than 0.054 for 5 the system of US5,522,228). This calculation was made using the system of US 5,522,228 as a basis as follows.

For the system of US 5,522,228 an assumption was made that there was 100g of each of zeolite and carbon in the vessel 11 and 10 respectively. The energy required to heat 10 carbon from 0°C to 30°C was estimated at around 2.1kJ. The energy required to heat the zeolite from 45°C to 70°C and from 70°C to 200°C was estimated at around 1.75kJ and 9.1kJ respectively. The energy removed due to cooling from -40°C to -50 was estimated to be around 0.7kJ. Ignoring the 15 energies required for cooling zeolite from 190°C to 45°C, from 200°C to 190°C and for heating carbon from -50°C to 0°C (ie. due to the possibility of recycling energy from the material being cooled to the material being heated), the COP was estimated to be $0.7/(2.1+1.75+9.1) = 0.054$.

20 Using a similar approach, the module of Figure 1 was calculated to have a COP of 0.22. The desorption cooling system of Figure 2 was then calculated to have a COP much higher than 0.22, attributed to the much greater homogeneous heating achieved in each of modules A and B, 25 together with less heat loss therefrom because of module containment within bank vessels 22.

EXAMPLE 2.

A demonstration unit was developed and tested for 30 evaluating:

1. Regenerator temperature optimization;
2. Cooling capacity in kJ;
3. Coefficient of performance (COP) or efficiency;
4. Extent of temperature drop achieved in a cycle;
- 35 5. Any effect on performance with time;

6. Possibility of flexing heating and cooling rates or time to enable design of an optimum time cycle for a commercial system.

A schematic diagram of the demonstration unit is
5 shown in Figures 3a&b, where like reference numerals are used to denote similar or like parts to those of Figures 1&2. The demonstration unit 40 comprised one of the two modules A and B as shown and described in Figure 2.

Experiments were performed to study and optimize one
10 of the modules to collect relevant performance and design data, and thereby enable scale up and scale down in the design of commercial modules.

The demonstration unit comprised 102 identical chiller modules 10 (as shown in Figure 1). The chiller
15 modules were stacked in insulated regenerator and desorption cooler chambers 26,28, with each chiller module conduit 16 extending through wall 24. In addition, insulated inlet 41,42,44 and outlet 46 ducts were provided to/from the chambers 26,28 to maximize heat transfer
20 efficiencies and minimize heat losses.

The regenerator chamber inlet was connected to a hot air source and an ambient air source. The hot air source comprised an electrical heater 48 in airflow communication with a coaxial fan 50 (Fan 2) to produce hot air at
25 various desired flow rates and temperatures. The ambient air source comprised another coaxial fan 52 (Fan 3). A manually operated damper 54 was employed between the hot air source and the ambient air source to selectively switch between hot and ambient air. The desorption cooler chamber 28 was also connected to an ambient air source
30 which comprised a third coaxial fan 56 (Fan 1).

Thermocouples were placed appropriately at regenerator inlet (T1,T8), regenerator outlet (T4), regenerator (T6), desorption cooler inlet (T3),
35 regenerator outlet (T4), and desorption cooler outlet (T5), to sense and continuously record temperature changes during operation. A data logging computer connected to the

thermocouples was used to record the temperatures during test runs.

Operation

- 5 The following steps were employed to achieve cooling of an air stream:
1. The data logging computer was switched on to record the temperature T at various locations as indicated on the unit 40 in Figure 3a.
 - 10 2. The damper 54 was manually switched to allow hot air flowing via the heater 48 into the regenerator 26, and then the fan 50 (Fan 2) and heater 48 were switched on.
 - 15 3. The fan 56 (Fan 1) was switched on to remove any heat generated due to adsorption in the desorption cooler chamber 28. During regeneration fan 52 (Fan 3) was switched off.
 - 20 4. Once the regenerator 26 acquired a temperature of 135-200°C and the desorption cooler 28 had cooled down to ambient temperature (20-25°C), the heater 48 and fan 50 were switched off. The damper was then manually switched to allow ambient air from fan 52 into the regenerator 26.
 - 25 5. In this regard, fan 52 was switched on whilst fan 56 continued running to produce cold air flowing out of desorption cooler 28.
- These steps completed one cycle of operation. It was noted that for eg. a commercial system, whilst Module A was regenerating Module B would produce a cooling effect and, once Module B stopped producing cold air, Module A would be activated to start producing cold air. In this way cold air could be produced continuously.

Although the demonstration unit was tested with air, it was noted that many other fluid streams could be used as a heating and/or cooling medium.

35 Operating Parameters and Results

During the test runs (see eg. Run # 76, Table 1 below) the regenerator 26 was heated with hot air at 150-

200°C (T₁, T₈) with a flow rate of about 250-300 litres/second. The air flow through the desorption cooler chamber 28 was maintained at around 250 litres/second.

Regeneration was considered complete when the air

5 temperature T₄ at the regenerator outlet 46 became the same as the inlet temperature T₁, T₈ of 150-200°C, and the regenerator temperature T₆ had reached around 120°C -150°C. To ensure complete regeneration, the heating was continued for a short extra time period (eg. 20-30 mins).

10 As shown in Figure 4, regeneration was complete within the first 30 minutes (ie. T₄ = T₈). In addition, after 30 minutes there was no significant change observed in the regenerator temperature T₆.

15 After regeneration, the heater 48 and fan 50 were switched off and the position of damper 54 was changed to allow ambient air from fan 52 to cool down the regenerator. During this time, the air flow rate via fan 52 was maintained at about 250-450 litres/second.

20 For most runs, the air flow via fan 56 into the desorption cooler 28 to produce cold exhaust air was kept at between 85-250 litres/second. As shown in Figure 5, a temperature drop between 5°C to 7°C (T₅) was observed in the desorption cooler exhaust air depending on the relative humidity of the air (which varied from 30% to 25%). It was also observed that, with no air flow through the desorption cooler chamber 28, the temperature of the chamber dropped by 11-14°C, depending on the ambient temperature.

25 The cooling cycle was considered complete when the inlet (T₃) and outlet (T₅) temperatures were the same (ie. greater than 100 mins in Figure 5). In addition, as indicated by Figure 5, the total cooling period was about 60 minutes. It was noted, however, that in practice only 30 minutes of peak cooling needed to be considered to 35 match with a 30 minute heating cycle.

The temperature plots of Figure 6 record a special run that comprised a 25 minute regeneration period and a

25 minute cooling period. The operating conditions are shown in Table 2 (below). It was found that an decreased regeneration air temperature of 150-170°C could be used without a significant loss of cooling capacity.

5 It should be noted that the inlet air temperature slightly increased during each run. This was partially due to heat released from the fan motor but was also due to a change in room temperature resulting from minor losses from the insulated surface of the heater, regenerator and
10 associated ducts.

The flow rates used for the trial runs were based on a heat transfer model. Air flow was estimated from the air velocity in a meter long 310mm internal diameter duct fitted at the inlet of each fan. A digital anemometer
15 (manufacturer Lutron, Model YK-2001AL) was used for velocity measurements. Relative humidity and temperature in the vicinity of the demonstration unit were measured using an electronic hygrometer (manufacturer Erler & Weinkauff) with $\pm 10\%$ accuracy.

20 Calibration and accuracy of the thermocouples were also tested on a regular basis. Temperatures were recorded up to the second place after the decimal and they had a maximum 10% error.

Based on the temperature and flow rates measured for
25 more than 50 trial runs, the cooling capacity of the desorption cooler was estimated to be around 900-1200 kJ, with the Coefficient of Performance (COP) varying between 0.07 to 0.12, depending on heat losses, humidity, efficiency of regeneration and measurement error. This
30 indicated that favourable performance could be achieved in a commercial scale-up. Tests were also conducted to optimize the operating conditions to achieve maximum cooling capacity and COP.

The performance of a single module was tested for
35 about 1 year and the demonstration unit was tested for more than six months, and no deterioration in performance in either case was observed.

Table 1 Operating conditions during run #76:

	Regeneration	Cooling
Air flow at Fan 1 (l/s)	105.6	105.6
Air flow at Fan 2, (l/s)	256.5	0
Air Flow at Fan 3 (l/s)	0	256.6
Regeneration mean inlet air temperature (°C)	200	23.58
Cooler mean inlet air temperature (°C)	22.59	23.58
Relative humidity (%)	62%	64%
Energy used in regeneration (kJ)	12811*	0
Energy removed during cooling (kJ)	0	1223*
Coefficient of performance	-	0.1*

* Humidity effect omitted when calculating these

Table 2 Operating conditions during run #87

	Regeneration	Cooling
Air flow at Fan 1 (l/s)	256.6	91
Air flow at Fan 2, (l/s)	309	0
Air Flow at Fan 3 (l/s)	0	450
Regeneration mean inlet air temperature (°C)	170	23.57
Cooler mean inlet air temperature (°C)	23.35	23.57
Relative humidity (%)	66%	66%
Energy used in regeneration (kJ)	11372*	0
Energy removed during cooling (kJ)	0	980*
Coefficient of performance	-	0.09*

5 * Humidity effect omitted when calculating these

It is to be understood that the preceding description of preferred methods, apparatus and systems, and the preceding Examples, are provided for illustrative purposes only, and are not intended to limit the scope of the invention in any way. Furthermore, it should be

appreciated that various other changes and modifications can be made to the embodiments, in addition to those already described, without departing from the basic inventive concept. All such variations and modifications
5 are to be considered within the scope of the present invention.

It is also to be understood that references to prior art information herein do not constitute an admission that the information forms part of the common general knowledge
10 in Australia or in any other country.